The Tacoma waterfront at sunset. *Courtesy City of Tacoma*

UNCERTAIN FUTURE

Consequences for Marine Ecosystem Structure and Function

Climate warming will shape the Puget Sound ecosystem from both the bottom-up (via impacts on phytoplankton and other marine plants that comprise the base of the food web) and the top-down (via direct impacts on top predators such as salmon and marine mammals). Taken together, these changes can be dramatic. In the coastal ocean, for example, broad reorganizations of the marine ecosystem have been associated with the subtle decade-to-decade changes in climate associated with the PDO.[53] This has resulted in salmon in the coastal waters of Washington, Oregon, California, British Columbia and Alaska returning in relatively large or small numbers, depending on the phase of the PDO.[54]

> *"The ultimate impact on each individual species that calls Puget Sound home will depend on how each of these changes reverberates across the food web."*

Future climate-related changes in the environment will be accompanied by changes in other factors such as human activities that are also very difficult to predict. The ultimate impact on each individual species that calls Puget Sound home will depend on how each of these changes reverberates across the food web, how each change interacts with every other change, and on the ecosystem's ability to adapt to a rapidly changing chain of estuarine and oceanic conditions.

The complex interrelationships among all of the living components of the Puget Sound ecosystem make detailed projections of the changes that may result from global warming impossible. In the following sections, we suggest how the projected changes already described (in water temperature, freshwater inflow, sea level rise, etc.) may affect individual components of the ecosystem, specifically plankton, fish and other animals, nearshore habitat and Puget Sound salmon.

Plankton

The base of the food chain includes benthic or bottom-dwelling algae and tiny floating algae called phytoplankton. Major changes in these populations have been observed over the last several decades that may have resulted from changes in climate and/or human influences.[55] Climatic influences on phytoplankton include variations in temperature and other water properties.

In Puget Sound, variations in temperature may be more important for phytoplankton than variations in freshwater input and mixing.[56] Thus a warming climate may increase surface productivity. Warmer temperatures would also alter the rates of processes in deep water, for example, increasing respiration,[57] which would decrease the concentration of oxygen in deep waters. Not only do changes in average temperature matter; changes in the amount that temperature varies over the year in any one location will also shape future ecosystem characteristics.[58]

Higher future levels of atmospheric CO_2 will also influence these dynamics. With uptake of CO_2, ocean water has become more acidic and will continue to do so.[59] This will alter water quality and consequently favor those plankton, fish and other marine organisms that tolerate more acidic water. Acidification will also make it more difficult for two important types of plankton—coccolithophores and foraminifera—to form their calcite shells. These changes are likely to be important to the food web, but in ways scientists cannot entirely predict.

Lake Washington: Uncoupling the predator-prey relationship

In the freshwater environment of the region's lakes, stratification is driven by temperature and there are indications of important changes linked to the effects of climate warming on stratification.

Long-term records show Lake Washington warming substantially since the 1960s.[60] Combined with variability in climate associated with the Pacific Decadal Oscillation (PDO), a warming climate has extended the period of summer stratification in Lake Washington from 1962 to 2002 by 25 days, mainly through earlier spring stratification (16 days).[61]

Warmer temperatures in the future may further increase the duration of summer stratification in Lake Washington.

In Lake Washington, the spring phytoplankton bloom (period of enhanced plant growth) has been occurring earlier in the year, reflecting the earlier timing of the spring transition to stratified or layered water conditions.

Some zooplankton species (the tiny creatures that feed on phytoplankton) have adjusted to this change in timing while others have not. For example, the bloom timing of the species *daphnia* has not changed. This has resulted in a growing gap between the timing of the spring peak of zooplankton and that of the phytoplankton on which they depend.[62]

The shift in this previously well-timed interaction between a predator and prey may have severe consequences for the entire ecosystem if climate continues to warm.

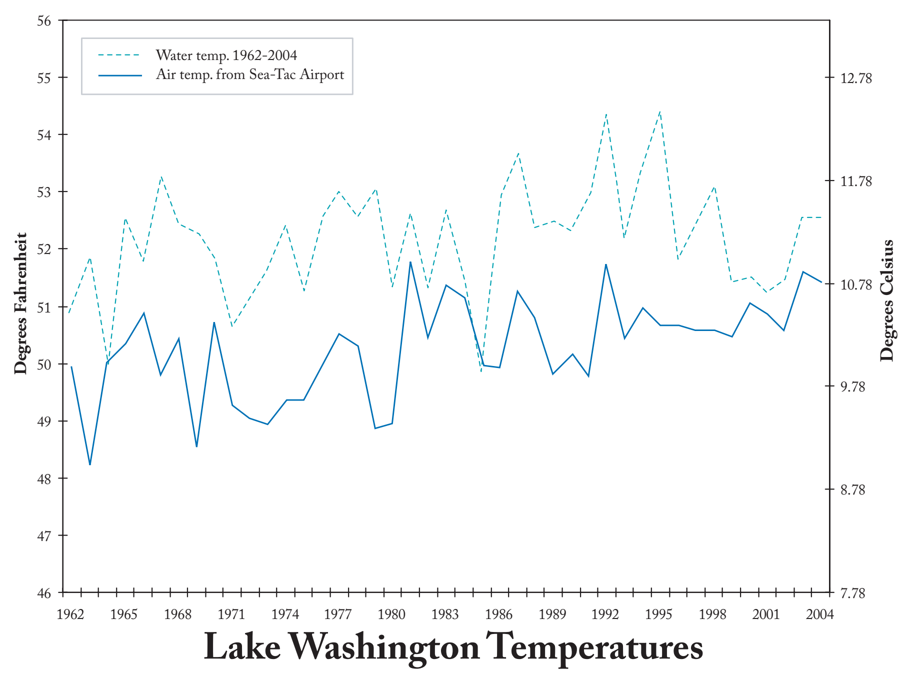

Figure 9: Observed trends in Lake Washington temperatures. The solid line shows annual average water temperature (0-200 feet, or 0-60 m) from 1962 to 2004. The dashed line shows annual average air temperatures from Sea-Tac Airport for comparison.[82]

Puget Sound shellfish. *Rae A. McNally*

Shellfish and harmful algal blooms

Puget Sound is one of the largest shellfish-producing regions in the United States.[63] Puget Sound shellfish are vulnerable to contamination by the toxics produced by harmful algal blooms. Toxic blooms can lead to closure of commercial and recreational shellfish beds to protect the public against paralytic shellfish poisoning (PSP), a potentially fatal illness caused by eating contaminated shellfish, and domoic acid poisoning (DAP), which can cause temporary or permanent memory loss.

Concentrations of toxins in Puget Sound shellfish and the geographical scope of shellfish closures have increased over the past four-to-five decades.[64] There has been a slow progression of PSP toxins from northern to southern areas of Puget Sound. Since the 1980s, the frequency of detection of PSP toxins has increased in the southern basins of Puget Sound, an area containing the region's most productive shellfish beaches. Public beaches can also be affected by these pathogens. DAP has only been observed much more recently; the first closure of a Puget Sound beach due to DAP occurred at Fort Flagler (near Port Townsend) in 2003. The most recent inland waters DAP-related shellfish closure took place in September 2005 in Sequim Bay.

Growing human development of the Puget Sound region is likely a major contributor of the recent increases in PSP toxins. Increased nutrients (via activities such as aerial forest fertilizing, sewage outfalls and agricultural runoff) can provide more favorable growth conditions for the algae producing PSP toxins. Those algae also respond favorably to stratified conditions, while the algae that produce domoic acid are thought to be favored by well-mixed environments and warmer temperatures.[65]

Climate change could increase the viability of some organisms responsible for harmful algal blooms in Puget Sound. Increased winter stratification of water may encourage more PSP-causing algae. Warmer temperatures may yield more DAP-causing algae, but increased winter stratification may have the opposite effect. The ultimate magnitude and frequency of future harmful algal blooms will depend on environmental changes and human use of Puget Sound.

Salt marshes

Salt marshes are highly productive habitats found near river mouths where fresh and saltwater mix. Salt marshes support a mix of plant and animal species, including shrimp, crabs, salmon, terns and herons. The plants filter suspended sediments and nutrients, regulate dissolved oxygen in the water column, stabilize bottom sediments, and even reduce flooding by retaining stormwater during high-flow periods.

Salt marsh growth and distribution are affected by sea level, salinity, temperature, freshwater inputs, tidal flooding, and the physical characteristics of the landscape. Human factors, predominantly draining, diking, dredging, filling, erosion, pollution and dams, have contributed to an estimated 73-percent decline in salt marsh habitats since the mid-1800s with the most acute losses (near 100 percent) in heavily urbanized central Puget Sound.[66]

During the modest sea level rise of the 20th century, most remaining salt marshes were able to keep pace through accretion or the accumulation of sediments, generally rising as a result of sediment capture.[67] Twenty-first century sea level rise may lead to further loss of salt marsh habitat, particularly where land areas are already sinking (i.e., central and southern Puget Sound) and/or where sediment supply is reduced or where upland migration of marshes is prevented by shoreline armoring, coastal development or natural bluffs, for example.

Nearshore habitat

Sea level rise will affect many physical processes important for determining nearshore habitat characteristics above and beyond salt marsh conditions. Sea level rise is likely to increase both the pace and extent of Puget Sound shorelines threatened by slow, chronic erosion. At the same time, landslides along Puget Sound bluffs may increase because of the heavier winter rainfall projected by nearly all of the global climate models. These two changes would likely exacerbate each other.

The ultimate consequences for nearshore habitat will depend in a large part on how communities and citizens respond to these changes. Increased coastal armoring (e.g., bulkhead installation) can provide short-term local shoreline protection but is likely to have negative downstream effects on nearby beaches and limit the adaptability of wetland and eelgrass habitat.[68]

Climate change will also affect biological processes important for nearshore habitat. Changes in water temperature, water salinity, or soil salinity beyond the tolerance of certain plants could change the mix of plant species in salt marshes and the viability of invertebrates (e.g., crab, shrimp and sponges) that play a key role in the health and functioning of nearshore systems. Changes in precipitation could change nutrient loading and sediment accumulation. Increases in atmospheric CO_2 levels may stimulate growth in some nearshore plants.[69]

The degree to which any of these changes affect Puget Sound nearshore areas will vary with the specific characteristics of the ecosystem, its location in the Sound, its freshwater sources and the dynamics of the Sound in that particular area.

Diver surrounded by eelgrass. *John Southard*

Sensitive eelgrass and bull kelp systems

Eelgrass, found in shallow water to a depth of about 22 feet (around 7 meters), provides valuable habitat and food for many marine species, including herring, juvenile cod and salmon, sole, flounder and invertebrates. Eelgrass also provides valuable erosion control along the Puget Sound coastline by absorbing wave energy. As with salt marshes, human factors have reduced eelgrass beds by perhaps 33 percent.[70]

Climate-driven factors influencing eelgrass are sea level, temperature and salinity. These factors help determine where and how abundantly eelgrass grows: it prefers high salinity and low summer temperatures.[71]

Lower spring stream flow increases Puget Sound salinity and decreases suspended solids, factors that tend to increase eelgrass growth. Studies in Puget Sound have found that optimal eelgrass productivity occurs within a narrow range of temperatures—between 41-46°F (5-8°C).[72]

Climate warming may favor eelgrass growth by shifting stream flow from the growing season (spring and summer) to the winter, but these benefits would be minimized if water temperatures regularly exceed 59°F (15°C)—the temperature at which eelgrass becomes stressed[73]—or if rising seas result in a sufficient reduction in available light for photosynthesis.

Increasingly armored shorelines also could reduce areas of eelgrass through changes in sediment delivery and increased water depth.

Warmer water temperatures may also negatively affect Puget Sound kelp, another important subtidal plant that provides critical nearshore habitat. On the other hand, both eelgrass and bull kelp may benefit from higher concentrations of atmospheric CO_2. Laboratory experiments indicate that when exposed to seawater containing higher levels of CO_2, growth increases.[74]

Additional study is needed to assess how these competing factors will ultimately affect eelgrass and bull kelp systems.

E. Fork of Chimacum Creek. / Al Latham

Salmon in a warming world

All seven species of Pacific salmon and anadromous bull trout live within the Puget Sound Basin. In most river basins, wild populations are severely depleted and hatcheries operate to supplement wild runs in order to sustain salmon fisheries. Several stocks have been listed or are being considered for listing under the federal Endangered Species Act.

Although the picture is generally bleak, some positive exceptions can be found. Over the last three decades, for example, the chum salmon populations of Puget Sound have increased to the point that they are now the most abundant salmon species in the region.[79]

The causes of salmon decline have been summarized as the "four H's": Habitat, Hydropower, Harvest and Hatcheries. Climate is an important factor in anadromous fish habitat at every stage of their lifecycle. Because of differences in life history and habitat among the different stocks and species of salmon, steelhead and trout, the same climate events can affect different stocks and species in different ways.

For example, the same ocean conditions have been good for some stocks and bad for others. According to data collected by the Washington Department of Fish and Wildlife's science division, for example, marine survival rates for south Puget Sound coho have plummeted in recent years while marine survival rates for coho in the main basin of Puget Sound and Hood Canal have been relatively high.

The general picture of climate change for the Puget Sound—increased winter flooding and decreased summer and fall stream flows, along with elevated warm season stream and estuary temperatures —would be especially problematic for instream and estuarine habitat for salmon in the Puget Sound region.

Although most impacts of climate change look negative for salmon, a positive change could result from warmer stream temperatures in periods (generally during the cold season) that are now cooler than is optimal for rearing juvenile salmon and/or incubating eggs. Positive changes such as this, which apply to individual life history stages, could be cancelled out by negative changes prevalent during other periods of the salmon's life.

Future coastal oceanographic conditions could conceivably change in positive ways for salmon, but the nature of these changes is highly uncertain because of the close dependence on uncertain future changes in coastal winds.

Fish and other animals

Fish and other animals will be affected by climate change in many ways—directly via changes in habitat and indirectly via changes in the availability of food.

Temperature is a dominant controlling factor of growth rates of most cold-blooded marine organisms. Increasing water temperatures can increase growth rates, providing many benefits, but only to a certain point.[75] Temperatures that are too warm can stress an organism, causing decreased growth and survival and weakened immune systems, which have been linked to disease epidemics in marine populations (e.g., sea urchins) and seabirds and disease-related marine mammal strandings.[76]

The consequences of warmer temperatures may be especially severe for species unable to seek out cooler temperatures, especially at vulnerable life stages. For this reason, increasing water temperatures above the optimum level for stationary shellfish, for example, could have more severe impacts than increasing water temperatures above the optimum level for salmon that could presumably move to pockets of cooler water.

Still, salmon experience thermal barriers to migration when stream and estuary temperatures reach approximately 70-72˚F (21-22˚C).[77] The number of days when water temperatures in the Ship Canal exceeded 68˚F (20˚C) in summer has clearly increased since 1974. From 1974 to 1981, the number of summer days when temperature exceeded the threshold ranged from a low of 15 to a high of 48. All summers from 1983 to 1998 had more than 48 days warmer than the threshold, with an average of 68 high-temperature days and a maximum of 87 in 1992.[78]

Many migratory birds pass through Puget Sound for food and shelter on their routes. They will be affected here and elsewhere as climate change alters the availability of food and habitat.

Jennifer Vanderhoof

Small marine organisms such as the feather duster worm could be affected by climate change in many ways—directly via changes in habitat and indirectly via changes in the availability of food. The consequences of warmer temperatures may be especially severe for species unable to seek out cooler temperatures, especially at vulnerable life stages.